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Published in:
Optics Express

Link to article, DOI:
[10.1364/OE.18.00A272](https://doi.org/10.1364/OE.18.00A272)

Publication date:
2010

Document Version
Publisher's PDF, also known as Version of record

[Link back to DTU Orbit](#)

Citation (APA):
Medford, A. J., Lilliedal, M. R., Jørgensen, M., Aarø, D., Pakalski, H., Fyenbo, J., & Krebs, F. C. (2010). Grid-connected polymer solar panels: initial considerations of cost, lifetime, and practicality. *Optics Express*, 18(S3), A272-A285. <https://doi.org/10.1364/OE.18.00A272>

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Grid-connected polymer solar panels: initial considerations of cost, lifetime, and practicality

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Abstract: Large solar panels were constructed from polymer solar cell modules prepared using full roll-to-roll (R2R) manufacture based on the previously published ProcessOne. The individual flexible polymer solar modules comprising multiple serially connected single cell stripes were joined electrically and laminated between a 4 mm tempered glass window and black Tetlar foil using two sheets of 0.5 mm thick ethylene vinyl acetate (EVA). The panels produced up to 8 W with solar irradiance of $\sim 960 \text{ W m}^{-2}$, and had outer dimensions of 1 m x 1.7 m with active areas up to 9180 cm^2 . Panels were mounted on a tracking station and their output was grid connected between testing. Several generations of polymer solar cells and panel constructions were tested in this context to optimize the production of polymer solar panels. Cells lacking a R2R barrier layer were found to degrade due to diffusion of oxygen after less than a month, while R2R encapsulated cells showed around 50% degradation after 6 months but suffered from poor performance due to de-lamination during panel production. A third generation of panels with various barrier layers was produced to optimize the choice of barrier foil and it was found that the inclusion of a thin protective foil between the cell and the barrier foil is critical. The findings provide a preliminary foundation for the production and optimization of large-area polymer solar panels and also enabled a cost analysis of solar panels based on polymer solar cells.

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OCIS codes: (350.6050) Solar energy; (220.4840) Testing; (310.6845) Thin film devices and applications; (040.5350) Photovoltaic; (160.0160) Materials; (160.4890) Organic materials; (160.5140) Photoconductive materials; (250.2080) Polymer active devices. Electricity grid connection, panel production, polymer solar cells, R2R manufactured OPV, large area, glass encapsulation

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1. Introduction

Polymer solar cell technology [1–7] has evolved from a level where large laboratory scale devices could be manufactured [8–12] to its current stage where industrial manufacture in large volume using roll-to-roll (R2R) processing methods is possible [13–18]. Most recently the technology has been incorporated into flexible electronic products [19–21] and has been demonstrated by many groups in round robin studies [22]. The ultimate goal for the technology is, however, to compete with existing photovoltaic technologies for electrical energy production for grid or off-grid applications [23]. There is an interest in establishing the requirements for polymer solar cells to become suitable for grid connected applications such that future research may drive the technology towards this goal.

In this work we detail our experience with the manufacture of large-area polymer solar panels using standard encapsulation techniques currently used for crystalline silicon based photovoltaics. The process is shown schematically in Fig. 1(a), which also defines the terminology for solar cells/modules/panels as used in the context of this article. We describe experiences with grid connection and fabrication of the polymer solar panels and report their stability in an outdoor environment.

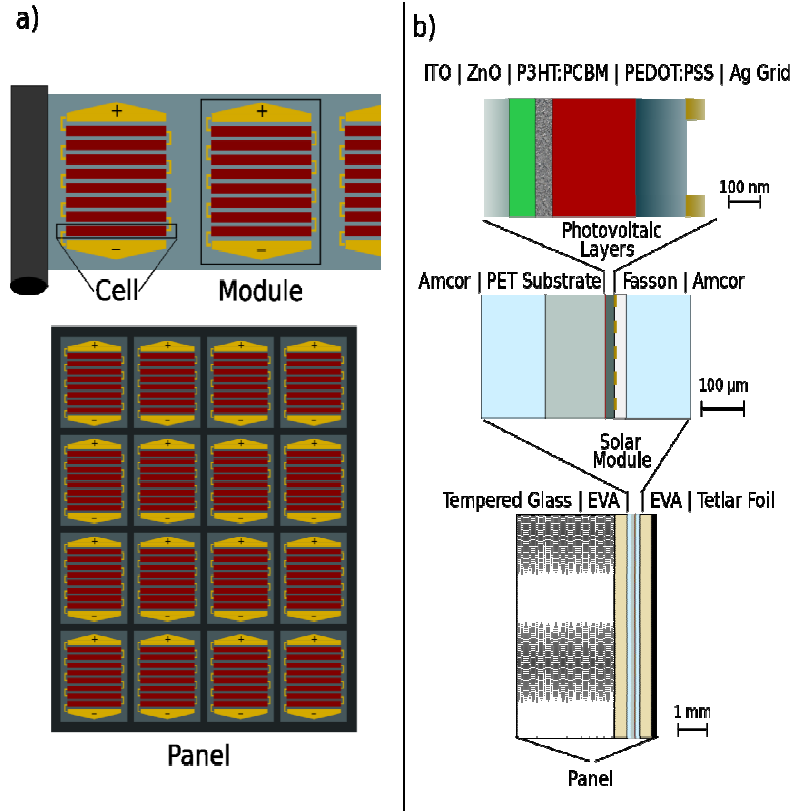


Fig. 1. (a) Schematic of process to convert R2R coated polymer solar cells into full size solar panels. Actual number of cells per module and modules per panel differs from that shown in the diagram. (b) Schematic (approximately to scale) of the layer structure for the panel, module, and solar cell. Amcor and Fasson refer to commercial PET encapsulation layers as described in the experimental details.

2. Experimental procedure and methodology

2.1 Manufacture of polymer solar cells

Polymer solar panels were produced in three generations (GEN1, GEN2, GEN3). The modules used for each generation varied slightly, but all were produced following the previously reported ProcessOne [14]. The device structure of the active stack was Polyethylene terephthalate (PET) – Indium-doped tin oxide (ITO) – Zinc Oxide (ZnO) – Poly(3-hexylthiophene): Phenyl-C61-butyric acid methyl ester (P3HT:PCBM) - Poly(3,4-ethylenedioxythiophene): poly(styrenesulfonate) (PEDOT:PSS) – Silver (Ag) grid as shown in Fig. 1(b). Flexible PET foil sputtered with ITO (~80 nm thickness) was cleaned with isopropanol prior to coating. For GEN1 and GEN2 a nanoparticulate ZnO layer was deposited from a previously reported solution [14]. GEN3 used a thin-film ZnO layer [18]. P3HT:PCBM were either dissolved in a mixture of 1,2-dichlorobenzene (DCB) and chloroform with a concentration of 24 mg ml⁻¹ P3HT and 22 mg ml⁻¹ PCBM (GEN1) or dissolved in chlorobenzene (CB) with a concentration of 15 mg ml⁻¹ P3HT and 12 mg ml⁻¹ PCBM (GEN2, GEN3) [18]. PEDOT:PSS was purchased from Agfa (EL-P 5010) and diluted with isopropanol, and the silver ink (PV410) was used as-purchased from Dupont.

Modules for GEN1 and GEN3 consisted of 16 serially connected single cells (0.9 x 25 cm²) amounting to a total active area of 360 cm²/module. The total module size was 25 x 27 cm² corresponding to 53% coverage. Modules for GEN2 consisted of 12 serially connected

single cells ($1.7 \times 25 \text{ cm}^2$) which sums to an active area of 510 cm^2 / module (75% coverage). Power conversion efficiencies are calculated based on active areas.

The primary difference in the module generations was the encapsulation procedure. Modules in the GEN1 panels had only a thin $25 \mu\text{m}$ PET lamination foil with $\sim 5 \mu\text{m}$ acrylic adhesive purchased from Fasson Roll Materials (Fasson barrier) on top of the silver electrode, while the GEN2 panels lacked this Fasson barrier but instead employed a $\sim 100 \mu\text{m}$ PET gas barrier layer purchased from Amcor Flexibles with $\sim 50 \mu\text{m}$ pressure-sensitive acrylic adhesive purchased from 3M [19–22] which included a filter to attenuate UV radiation below 390 nm (Amcor barrier). The barrier layer was varied for the GEN3 panels, as listed in Table 1. Modules used in the GEN2 panels were photo-annealed by exposing them to artificial sunlight (KHS solar constant 575, 1000 Wm^{-2}) for 40-60 minutes to remove any inflection point [18,22,24] and ensure maximum initial performance. The modules for both GEN2 and GEN3 were characterized prior to panel incorporation by taking *IV* curves using a Keithley 2400 series source meter and artificial sunlight (KHS solar constant 575, 1000 Wm^{-2}). The structure of modules for each generation is summarized in Table 2.

Table 1. Structure of polymer solar modules from various generations

Panel Type	Amcor Barrier	Fasson Barrier	Active Layer	ZnO layer	Module geometry (coverage)
GEN1	None	Yes	P3HT:PCBM in DCB + chloroform	Nanoparticle	$16 \times 0.9 \text{ cm} \times 25 \text{ cm}$ (53%)
GEN2	4-ply + UV filter ^a	No	P3HT:PCBM in CB	Nanoparticle	$12 \times 1.7 \text{ cm} \times 25 \text{ cm}$ (75%)
GEN3 ^b	3-ply 4-ply + UV filter ^a 6-ply	No	12:11 P3HT:PCBM in CB	Thin-film	$16 \times 0.9 \text{ cm} \times 25 \text{ cm}$ (53%)

^a <5% transmission below 390 nm

^b Large-area panels only. Details for small-area panels are given in Table 4.

2.2 Serial connection, lamination and encapsulation into large panels

Large-area solar panels ($1 \times 1.7 \text{ m}^2$) were produced for all generations. GEN1 and GEN3 large panels consisted of 24 individual modules per panel which were connected as 4 parallel-connected sets of 6 modules in series. The total active area for such panels is 8640 cm^2 (51% panel coverage). The GEN2 panel contained 18 modules connected as 2 parallel-connected sets of 9 modules in series. The active area for these panels was 9180 cm^2 (54% panel coverage). Additionally, small-area panels ($0.5 \times 0.6 \text{ m}^2$) were produced for GEN3 to investigate the influence of barrier layer on panel lamination. These panels consisted of 4 series-connected modules amounting to a total active area of 1440 cm^2 (48% panel coverage).

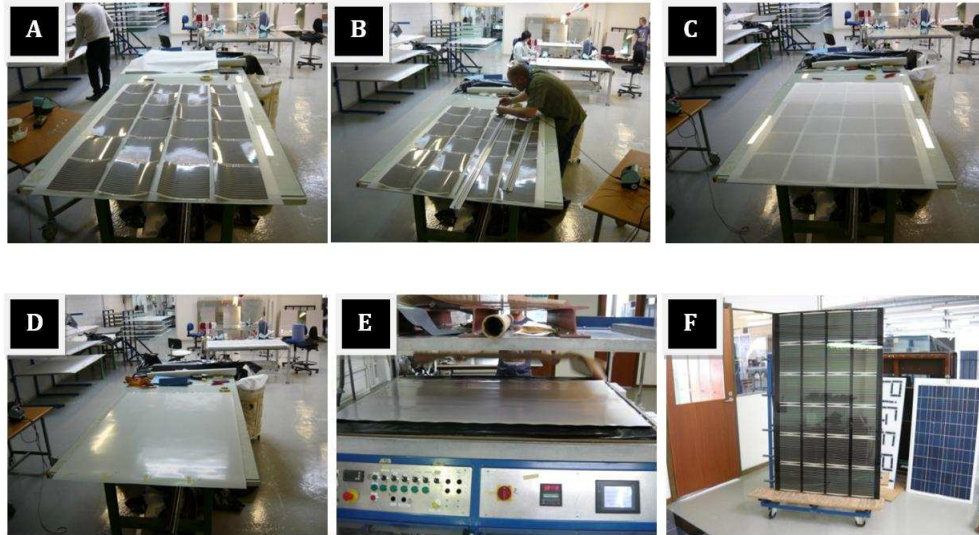


Fig. 2. The assembly of the module starts with laying the modules onto a glass panel covered with an EVA laminate sheet (a), after which electrical contacts are soldered onto the polymer modules (b). An EVA laminate sheet is placed over the modules (c) and a tetlar backing foil (black underside) is placed above the EVA (d). The panel is then heated to 150 °C for 30 minutes melting the EVA and laminating/securing the modules (e). After cooling the panel is completed (f).

The general procedure for encapsulating the polymer solar modules in the glass panel is outlined in Fig. 2. The front tempered-glass panel was first laid on a flat table and cleaned carefully with ethanol. A sheet of EVA was placed onto the glass, ensuring that the edges were aligned. Solar modules were arrayed across the EVA as desired [Fig. 2(a)] with care being taken to properly align electrodes. Flat copper ribbon pre-coated with solder were used to make electrical contact between modules [Fig. 2(b)]. The solder time was optimized such that a good connection was made but the contact was not destroyed due to melting of the plastic under the module electrode. Series/parallel connections were made as-desired, and extra wires were added to ensure that the contacts were in a convenient position on the panel (in the center of the upper edge). After completion of soldering another layer of EVA was placed over the cells [Fig. 2(c)]. Black Tetlar backing foil was then placed face-down over the EVA layer [Fig. 2(d)]. The Tetlar foil was slightly bigger than the panel, and was placed such that the overlap was approximately equal on all sides. Small slits in the EVA and backing foil were made over the position of the electrical contact, and the wires were pulled through so that they could be accessed after lamination. Masking tape was placed over the slits to keep the EVA from leaking out. Finally, the assembly was moved to the vacuum laminator [Fig. 2(e)]. The panels were heated under a vacuum of 0.1 mBar at 130 °C (GEN1, GEN3) or 150 °C (GEN2) for 30 minutes causing the EVA sheet to liquefy. This sealed the cells in place and secured the panel together. After lamination the panels were completed [Fig. 2(f)]. Completed panels were sealed inside a weatherproof aluminium frame using silicone sealant in a procedure analogous to that used for silicon solar panels. GEN2 and GEN3 panels included a weatherproof box around the electrical contacts to minimize their exposure to moisture.

2.3 Outdoor Testing

The polymer solar panels were mounted outdoors on a solar tracker to evaluate their performance and stability under real conditions as shown in Fig. 3. GEN1 panels were mounted on April 17, 2009 and tested for the following 24 days. During this period the solar irradiance was stable at $\sim 960 \text{ Wm}^{-2}$ around mid-day on most days, and the testing setup

allowed the panels and solar irradiation to be monitored continuously. The GEN2 panels were first mounted on October 15, 2009 and were last tested in March 2010 amounting to a total of ~6 months outdoors. The weather was relatively warm (~10-15 °C) during the first 2 months, but stayed quite cold (<0 °C) during the last 4 months. The panels were also exposed to snow for around 2 months [Fig. 3(b)]. Unfortunately there were very few days where the solar irradiance reached ~960 Wm⁻² during the 6 months the GEN2 panels were placed outside, and for this reason their performance was monitored only at long intervals. Large-area GEN3 panels were mounted and connected to the grid on April 27 2010. *IV* characterization was carried out periodically throughout the study whenever the solar irradiance reached ~960 Wm⁻².

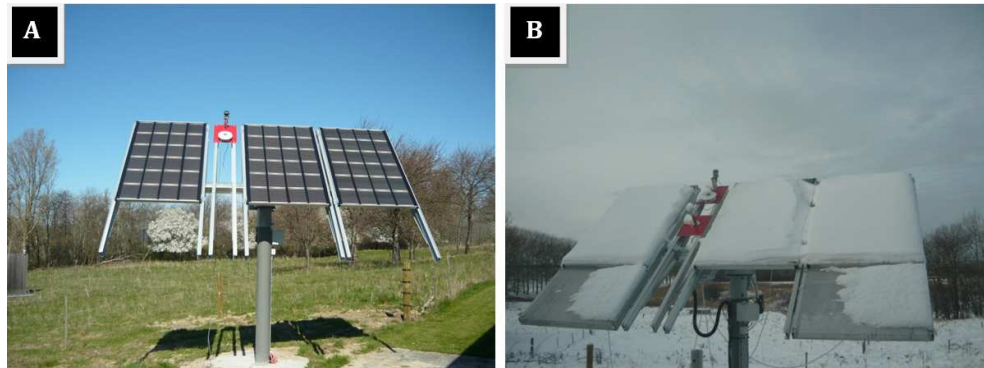


Fig. 3. Outdoor testing of the GEN1 (left) and GEN2 (right) solar panels on a tracking station showing seasonal variation.

2.4 *IV Characterization*

The electrical connection scheme allows for the panels to be temporarily disconnected from the grid and connected instead to a sourcemeter. A Keithley 2400 series sourcemeter and custom software was used to obtain *IV* data for the panels. The *IV* curves were taken from -5 V to slightly above the open-circuit voltage (40-50 V) for all panels with a resolution of 500 mV. The power conversion efficiency was calculated using the nominal active area of the modules and the solar irradiance as determined by a precision pyranometer from Eppeley Laboratories also mounted on the solar tracker.

2.5 *Grid connection*

During the GEN3 studies, the GEN3 panels were left constantly connected to the grid along with the degraded GEN2 panel which was still capable of generating some power. The solar panels were connected to the grid through OK4E-100 inverters from NKF electronics. The inverters are capable of handling 100 W and accept a DC input from 24 to 50 V_{DC}. When connected to the grid they supply 230 V_{AC} (50 Hz). Four independent OK4E-100 inverters were connected to the panels on the DC-side and to an electricity meter (ABB Automation Technology Products) on the AC-side through a high frequency induction earth leakage relay. The electricity meter had a resolution of 0.01 kWh and had a binary optical output of 10.000 peaks kWh⁻¹.

3. Results

3.1 *Cost analysis*

The cost of production of the polymer solar panels reported is outlined in Table 2. The total cost of the panel amounted to 300.00 € on a lab scale, which is fairly competitive with the cost of silicon panels (350-500 €/panel). However, when the cost is normalized to power produced

the price for the polymer panels is still above 36 €/W_p even under the best recorded conditions.

**Table 2. Cost estimates of producing a 1 x 1.7 m² panel under laboratory conditions.
Panel contains 24 modules with a total active area of 8640 cm² (51% coverage)**

Material	Materials Cost [€/panel]	Processing Cost [€/panel]	Total [€/panel]
PET-ITO	62.58	5.07	67.65
ZnO	1.40	4.00	5.40
P3HT:PCBM	10.78	4.00	14.78
PEDOT:PSS	5.55	4.00	9.55
Silver	9.89	4.00	9.55
Encapsulation ^a	15.58	1.52	17.10
Panel ^b	94.54 ^c	80.00	174.54
Total	174.38	102.59	298.57

^a Encapsulation cost includes barrier layer material (10.98 €/panel) and pressure sensitive adhesive (4.60 €/panel).

^b Panel cost includes glass (33.77 €/panel), Tetlar foil (11.25 €/panel), EVA foil (18.00 €/panel), silicon sealant (1.32 €/panel), aluminum frame (12.98 €/panel), aluminum corner pieces (4.64 €/panel), and a weatherproof connection box (12.58 €/panel).

^c Panel material cost will not scale linearly with area since the aluminum corner pieces and weatherproof box are required per panel rather than per unit area.

This is extremely expensive when compared to the price of 1-3 €/W_p for silicon panels, especially when it is considered that the silicon panels are stable to 80% of their initial performance for over 20 years while the stability of the polymer panels falls to nearly 50% after only 6 months.

3.2 Performance & Stability

3.2.1 GEN1 Panels

The GEN1 panels were first connected on April 17, 2009 and a lifetime study of the best panel was conducted over the following 24 days; the results are shown in Fig. 4. The panel output a maximum of 8 W on day 2, and decayed to below 80% of its initial performance after 7 days. The daily power output is plotted in Fig. 4(a), which sums to a total power output of 576.2 Wh over the lifetime of the panel. The efficiency of the panel over the lifetime study is also shown in Fig. 4(b). The panel had a maximum efficiency of 0.97% on day 2. Although the solar irradiance varied considerably at the end of the study, it is clear that the cell had degraded to approximately 20% of its initial performance after the 24 day study. The effects of cloud cover and other natural variables on the solar flux can be clearly seen as noise in the irradiance signal for many of the days, and the panel had electrical connection issues on day 11, resulting in disconnection after a few hours of illumination.

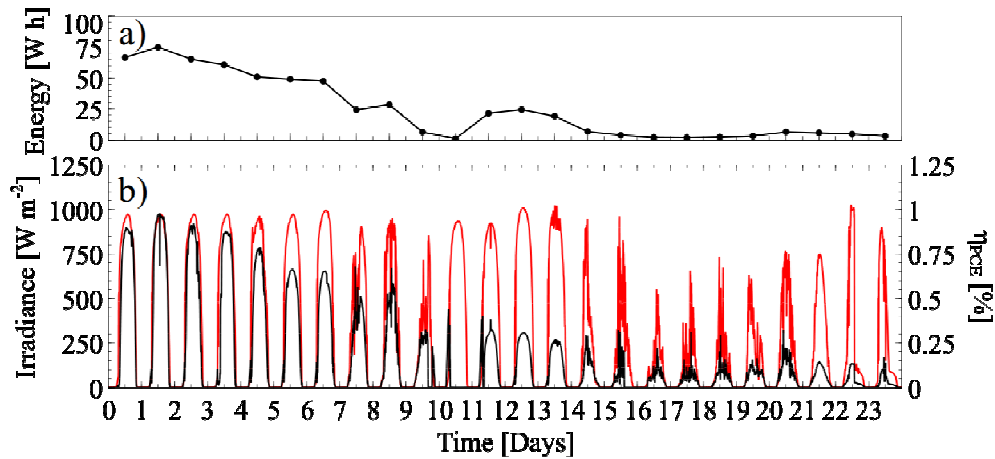


Fig. 4. Daily energy output (a) and performance stability (b) of GEN1 panels over a 24 day period. Red curve corresponds to solar irradiance (left axis), and black curve corresponds to power conversion efficiency (right axis).

The degradation of the panels was also examined in terms of the key parameters as shown in Fig. 5. The results show that the performance decrease was due mostly to declining current; the open circuit voltage (V_{oc}) remained relatively constant, and was still >30 V on day 23; similarly, the average fill factor (FF) remained around 30% for the duration of the study. The declining current is attributed to degradation of the photoactive layer due to oxygen diffusion through the thin Fasson barrier and UV exposure, although other mechanisms are also possible.

3.2.2 GEN2 Panels

Unfortunately, the GEN2 modules suffered severe delamination at the P3HT:PCBM-PEDOT:PSS interface during the high-temperature lamination step of the panels, and for this reason the performances were extremely poor; only one panel had a significant initial performance (0.3%). The panel was placed outside on October 17, 2009, but due to low solar intensities and poor panel performance it was not tested continually. The panel was left outdoors for 6 months during which the weather was cold and snowy (though not particularly sunny). After 6 months it was tested again and found to still be functional; the parameters as mounted and after 6 months are given in Table 3. The max power generated deteriorated to 50% of the initial, but this is very favorable when compared to the GEN1 panels which had deteriorated to 20% of its initial performance after only 24 days. The improvement is attributed to the additional Amcor barrier layer which decreases oxygen and water diffusion. It is also possible that the low solar flux over the lifetime of the GEN2 panels slowed their degradation since P3HT oxidation is known to be accelerated by light. Examining the parameters in Table 3 indicates that the loss of performance is still primarily due to a decreasing short-circuit current, which suggests degradation of the active layer.

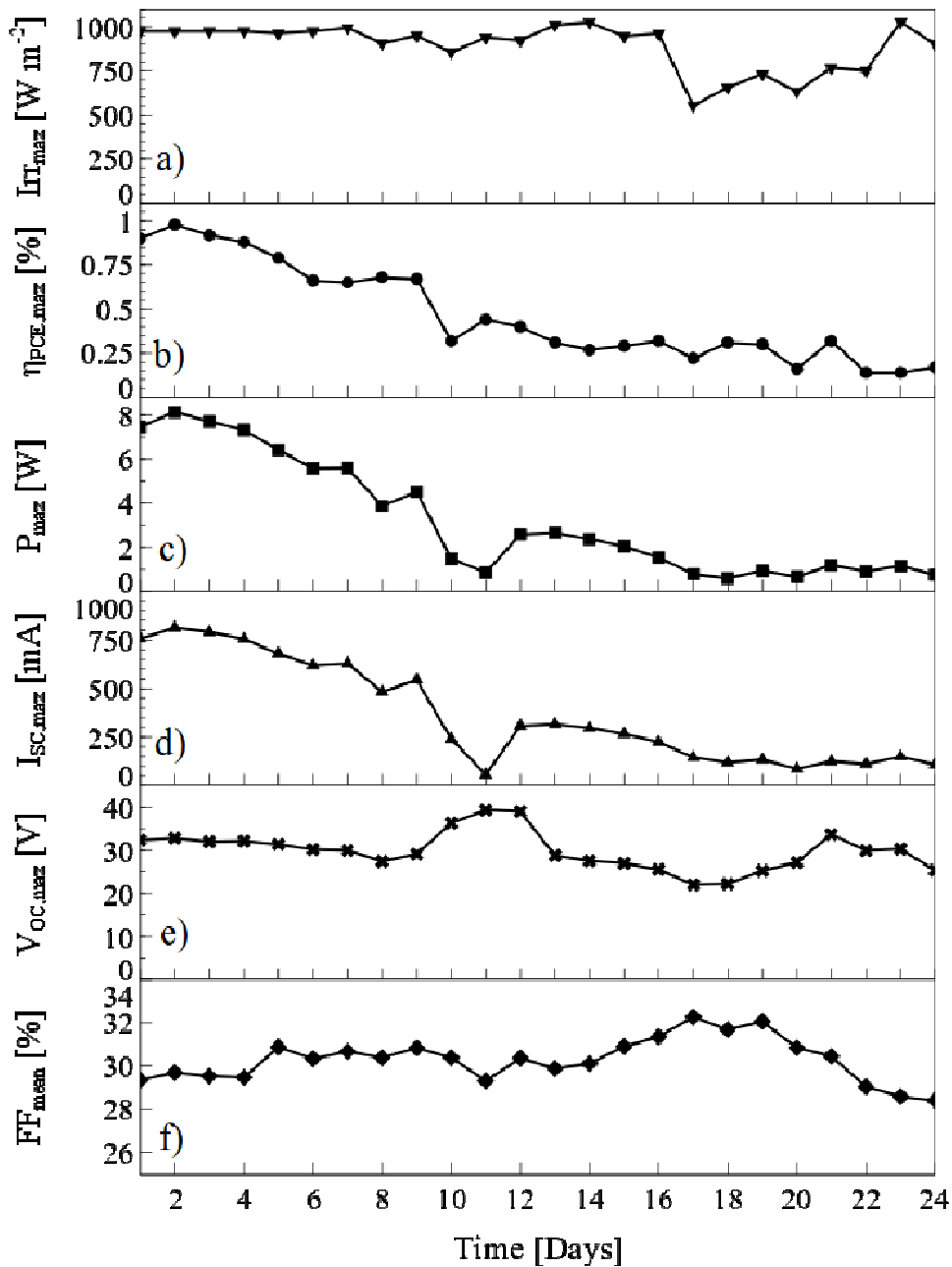


Fig. 5. Degradation of critical parameters for GEN1 panels over 24 day outdoor study. The daily max of each parameter is given (subscript max), with the exception of fill factor which is a daily average (subscript mean). The parameters from top to bottom are: (a) Solar Irradiance ($I_{rr,max}$), (b) power conversion efficiency ($\eta_{PCE,max}$), (c) max power (P_{max}), (d) short-circuit current ($I_{SC,max}$), (e) open circuit voltage ($V_{OC,max}$), (f) and fill factor (FF_{mean}).

3.2.3 GEN3 Panels

The GEN3 panels were prepared in several varieties in order to investigate the effects of different barrier layers and encapsulation procedures. Four small (4 module) panels were fabricated with several types of barriers as shown in Table 4. These panels were measured before and after lamination in order to evaluate the influence of various barrier layers on the lamination process. The best panel, GEN3-A, had a laminated power conversion efficiency around 1%, which is in agreement with the best power conversion efficiency obtained for the GEN1 panel. The other small panels had significantly lower performances, as listed in Table 4.

Table 3. Degradation of all parameters after 6 months for GEN2 panels

GEN2 Panels	Initial (October 2009)	Final (April 2010)	Percent of Initial (%)
PCE [%]	0.30	0.16	54
I _{sc} [mA]	141.6	88.0	62
V _{oc} [V]	53	51	96
Max Power [W]	2.45	1.33	54
Fill Factor [%]	32.7	29.5	90

In addition to these small experimental panels, two large 1 x 1.7 m² panels were produced from modules with a mixture of barrier types. These panels were grid-connected and monitored with *IV* curves when full solar irradiance (~960 Wm⁻²) was available for a total of 37 days. The initial performances of the panels were significantly lower than that of the best small panel because of differences in the encapsulation structure leading to loss of performance upon lamination. The initial power conversion efficiencies of the panels were 0.59% (3-ply half-panel), 0.41% (4-ply half-panel) and 0.37% (6-ply half-panel). The relative degradation of the panels (normalized to initial performance) is given in Fig. 6. It can be seen that all panels are above 80% of their initial performance after 37 days, and it is anticipated that the degradation will proceed slowly over the course of ~6 months as was observed for the GEN2 panels. Interestingly, there does not appear to be any significant difference between the 3-ply (black), 4-ply (blue) and 6-ply (red) panels. This implies that even the 3-ply barrier layer is sufficient to significantly slow oxygen diffusion, and is thus the best choice since it attenuates less light. Furthermore, neither the 3-ply or 6-ply Amcor encapsulation layers included a UV filter. The fact that there is no observable difference between these and the 4-ply barrier is attributed to an attenuation of UV by the tempered glass used in panel fabrication which is sufficient to suppress most of the UV induced degradation processes.

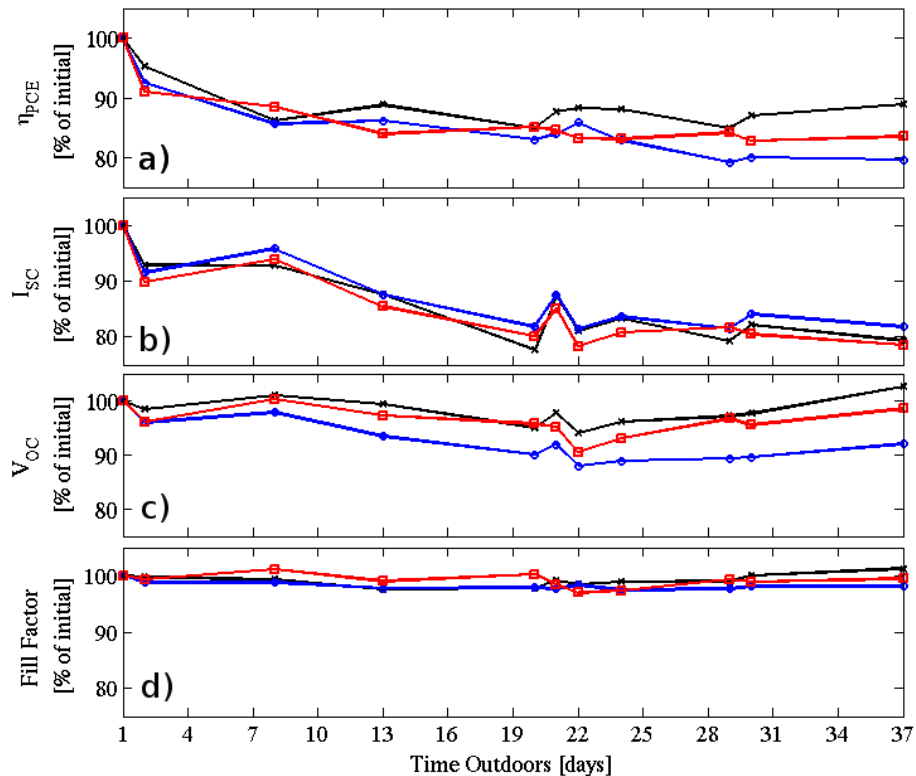


Fig. 6. Degradation of GEN3 panels made with modules encapsulated by 3-ply (black crosses), 4-ply (blue circles), and 6-ply (red squares) barrier layers. The parameters from top to bottom are: (a) power conversion efficiency, (b) short-circuit current, (c) open-circuit voltage, and (d) fill factor.

During the study the two large-area GEN3 panels as well as the degraded GEN2 panel were connected to the grid. Over the course of the study the 3 panels output a total of 3 kWh to the grid. This is inclusive of losses from operating at non-optimum voltage, and all losses in transmission, the inverter, etc. Based on the cost of € 300 per panel, this corresponds to a cost of ~200 €/W_{actual}. Although excessively high, it should be considered that this data comes from a lab-scale estimate of cost where one panel was already degraded to ~50% of its initial performance, and also during a period of weather with a lower than average solar flux. The cost is therefore a gross overestimate; however, it still reveals that enormous improvements are necessary to make polymer solar technology realistic.

4. Discussion

4.1 Optimization of panel fabrication

The GEN1 panels were fabricated with only the Fasson barrier on the individual modules designed to protect the active layer from physical damage; however, the barrier properties of the foil are not expected to be sufficient to prevent oxygen diffusion and the UV is not attenuated above 320 nm. The lamination of the panels did not result in any visible damage to the modules, and the initial performance of the panels was in good agreement with the module performance (~1% PCE). Unfortunately, the cells degraded beyond 50% of their initial performance after only 9 days outside. The degradation is attributed to a loss of activity in the photo-active layer due to a combination of oxygen diffusion through the very thin barrier and exposure to UV light. Severe bleaching of the active layer can clearly be seen in the degraded

cells (Fig. 7), and seems to occur preferentially over the Ag grid. It is hypothesized that the porous Ag grid acts as a transport channel which allows more rapid diffusion of oxygen in from the perimeter of the modules.

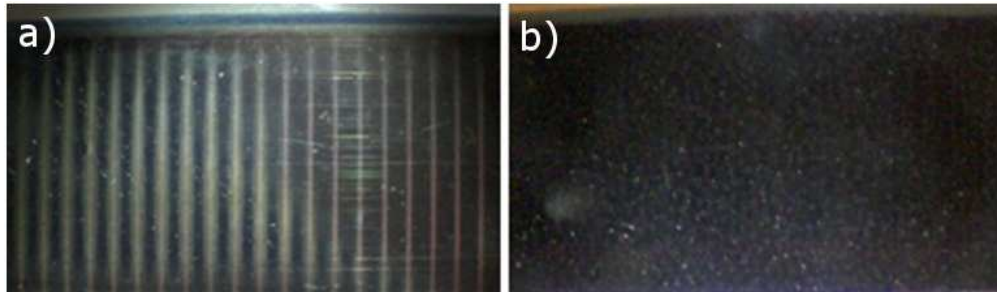


Fig. 7. GEN1 panel after 6 months showing bleaching over silver stripes (a) and the absence of bleaching in GEN2 panels after 6 months (b).

In order to increase panel lifetime the GEN2 modules were laminated with an Amcor PET barrier layer and 3M pressure-sensitive adhesive, but the thin protective foil was omitted to reduce processing steps. The barrier layer has reduced oxygen permeability, and also severely attenuates light with wavelengths below 390 nm (<5% transmission). The modules had power conversion efficiencies of $0.5 \pm 0.1\%$ when tested individually; however, upon panel lamination the modules were visibly delaminated at the P3HT:PCBM-PEDOT:PSS interface. Any area of de-lamination will not contribute to the photovoltaic response of the cell, and thus the actual active area is lower than the as-defined active area leading to a decreased PCE. It is also possible that chemical interactions between the barrier adhesive and the cell contributed to the loss of performance. It is hypothesized that de-lamination within the cells occurs due to the increased panel lamination temperature of 150 °C (compared to 130 °C for GEN1). Higher temperatures will cause the mechanical stresses due to thermal expansion to be greater within the active stack. From previous experiences with ProcessOne modules, the P3HT:PCBM-PEDOT:PSS interface seems to be the weakest interface and thus it is not surprising that it is the first to fail. Use of the thin Fasson barrier between the active layer and the barrier in GEN1 may also mitigate transfer of mechanical stress into the active stack and/or protect the active layer from the barrier adhesive. Despite this loss of performance upon lamination, the GEN2 panels showed no signs of bleaching after 6 months outdoors (Fig. 7). This supports that the preferential degradation over the Ag grid in the GEN1 panels is caused by some type of transport mechanism, or perhaps photochemistry involving UV below 390 nm.

From results of the GEN1 and GEN2 panels it was clear that the barrier layer has a profound effect on panel stability. The influence of barrier choice on the lamination step was investigated by creating 4 varieties of small (4 module) panels and comparing the panel performance to that of its constituent modules as shown in Table 4. The panel lamination temperature was also reduced to 130 °C which prevented cell de-lamination during fabrication.

Table 4. Barrier types for small GEN3 panels along with their performance before and immediately after panel lamination

Panel Type	Amcor Thickness	Fasson barrier	UV cutoff	Average Module PCE	Panel PCE	Percent of Module
GEN3-A	4-ply	Yes	390 nm	0.7 ± 0.06	0.97	139%
GEN3-B	4-ply	No	390 nm	1.2 ± 0.02	0.47	39%
GEN3-C	3-ply	No	320 nm	1.7 ± 0.07	0.73	43%
GEN3-D	6-ply	No	320 nm	1.5 ± 0.20	0.59	39%

From Table 4 it is obvious that the addition of the Fasson barrier between the active layer and Amcor barrier layer is critical when fabricating panels from the modules. When the Fasson barrier is included the performance increases after panel fabrication. This is likely due

to spectral mismatch between indoor module measurements and outdoor panel measurements, as similar increases have been observed when testing individual modules outdoors. Without the Fasson barrier the panel performance decreases to ~40% of the module performance. This is attributed to the differences in adhesives between the Fasson and Amcor barrier layers. There is surely some chemical difference between the proprietary adhesives and their solvents, and it is hypothesized that the 3M adhesive applied with the Amcor barrier releases chemicals during the hot melt lamination which damages the active layer upon heating. The fact that the Fasson barrier layer is thin (25 micron) with 5 micron adhesive in comparison to the adhesive employed with the barrier foil (50 micron) may also play some role in managing the mechanical stresses in the cell during panel lamination.

4.2 Improvements necessary for large-panel OPV success

From this demonstration of large-panel organic photovoltaics (OPVs) it is clear that massive improvements must be made before the technology can be competitive with silicon photovoltaics. The solution processability and low-cost of OPVs is often advertised as their major advantage, yet very few examples of solution processed cells exist, and the cost of current commercial products is not competitive with silicon [18,23]. Furthermore, the stability of OPVs is significantly poorer than silicon. It is often implied that if OPVs can reach an efficiency of 10% then the technology will become competitive at a large scale, but this still requires a reduction of cost and/or an increased stability when compared to silicon. The current status of OPVs indicates that the stability will never be competitive with silicon, meaning that cost reduction will be the only feasible strategy to make the technology competitive.

The distribution of cost by panel materials and components is given in Fig. 8. It is interesting to note that the cost of fabricating the modules into the panel actually exceeds the cost of producing the modules. It is also clear that ITO accounts for a large portion of the final costs. Although the panel cost (especially labor) is overestimated due to lab-scale production, it must be considered that the materials portion of this cost, which accounts for 27% of the total cost, will be similar for OPV and silicon panels. If this substantial fixed cost is included in the comparison it is apparent that OPV production must undergo even more substantial cost reduction in order to be competitive in the large-area panel market. This implies that other strategies should be pursued in the scale-up of OPVs which bypass the fabrication of panels. The mechanical robustness of polymer solar cells in comparison to silicon may allow for encapsulation and support setups which require far less post-production processes than the method presented here. Use of advanced flexible barrier layers may allow the polymer cells to be mounted directly to a rigid support, thus avoiding the majority of the panel cost. For example, if the cost of the cells is reduced by 50% (panel elimination, process optimization), the active area covers 75% of the panel (optimization of processing and print pattern) and an efficiency of 5% is achieved (already reported for lab-scale devices) then the cost would amount to 2.5 €/W_p. At this cost polymer solar panels could begin to compete with silicon panels in the short term; however, their stability is expected to be an order of magnitude below silicon, and they would require 4 times as much geometric area to generate the same amount of energy. These issues will significantly hinder OPV technology from competing in large-scale power generation schemes such as solar farms.

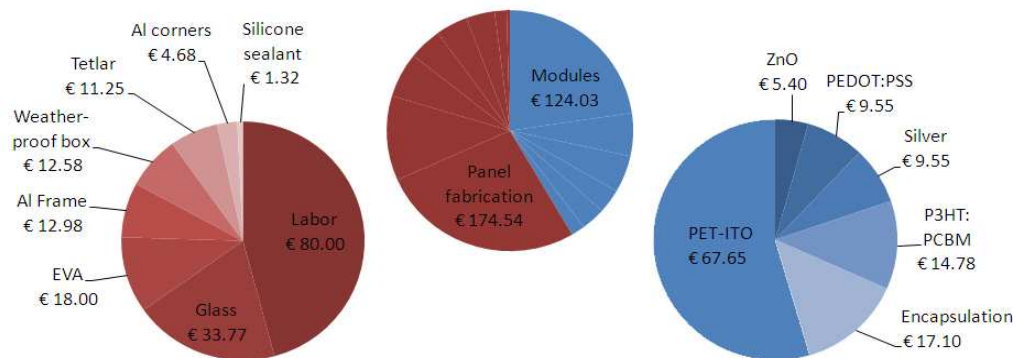


Fig. 8. Graphical representation of total cost of polymer solar panels (center), cost of panel fabrication (left) and cost of module production (right).

6. Conclusions

Large-area solar panels were fabricated from polymer solar cells and connected to the grid for the first time. The panels were created using methods and materials analogous to those used for silicon solar panels. Panel manufacture was optimized over 3 separate production runs. It was found that the choice of layer structure used to encapsulate the flexible polymer solar modules was the most critical parameter in preserving performance upon panel fabrication, and also plays a key role in panel stability. The best panel reached a maximum peak power of 8 W, and the final set of panels retained 80% performance for over 1 month. Panels were connected to the grid between testing, and generated a total of > 3 kWh during the study. A cost analysis revealed that the cost of power produced by polymer solar panels is currently more than one order of magnitude above the price of energy produced by silicon panels. The cost of incorporating the polymer cells into a rigid protective panel was found to be a major contribution to the total cost, implying that it is most beneficial to pursue strategies and applications where polymer solar cells are not used in traditional large-area panels. By focusing development on advanced encapsulation and processing techniques it may be possible to provide a place for polymer solar technology in applications such as off-grid generation in remote and developing locations [20] where their light weight and mechanical durability/flexibility overcome their low stability and large required area. However, due to concerns of stability and required area it is clear that if polymer solar cells are expected to rival silicon solar technology in large-scale power generation then significant obstacles must be overcome even if power conversion efficiencies of 10% are reached.

Acknowledgements

This work was supported by the Danish Strategic Research Council (DSF 2104-05-0052 and 2104-07-0022), EUDP (j. nr. 64009-0050). Andrew Medford is grateful for funding provided by the Danish-American Fulbright commission.